Lecture in Synchronous Generators

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Synchronous Generators

• Are the primary source of all electrical energy
• Commonly used to convert the mechanical power output of steam turbines, gas turbines, reciprocating engines, hydro turbines into electrical power for the grid
• Can be extremely large – power ratings up to 1500MW!!!
• Are known as synchronous machines because
they operate at synchronous speed (speed of rotor always matches supply frequency)
Lecture Outline

- Operating principle
- Physical construction of synchronous generators
- Synchronous generators under load
  - Isolated loads
  - The infinite bus
- Isolated loads
  - Regulation curves
- The infinite bus
– Synchronization
– Active and reactive power control

• Efficiency, size and power of electrical machines
Synchronous Generators: Operating Principle

- The rotor is mounted on a shaft driven by mechanical prime mover.
- A field winding (rotating or stationary) carries a DC current to produce a constant magnetic field.
- An AC voltage is induced in the 3-phase armature winding (stationary or rotating) to produce electrical...
power.

- The electrical frequency of the 3-phase output depends upon the mechanical speed and the number of poles
Types of Synchronous Generators

- Stationary field
- Revolving field
Stationary Field Synchronous Generator

• Poles on the stator (field winding) are supplied with DC to create a stationary magnetic field.
• Armature winding on rotor consists of a 3-phase winding whose terminals connect to 3 slip-rings on the shaft.
• Brushes connect the armature to the external 3-phase load
• This arrangement works for low power machines (<5kVA). For higher powers (& voltages), issues with
brushes and insulation of rotor windings.

- Therefore use revolving field...
Revolving Field Synchronous Generator

- Most common – also known as *alternator*
- Stationary armature with 3-phase winding on stator
- 3-phases directly connected to load
- Rotating magnetic field created by DC field winding on rotor, powered by slip-rings I brushes
Producing the DC field

• For both stationary and revolving fields, DC supply is normally produced by DC generator mounted on same shaft as rotor.
• Permanent magnets can also produce DC field – used increasingly in smaller machines as magnets get cheaper.
Synchronous Generator
Figure 16.1
Schematic diagram and cross-section view of a typical 500 MW synchronous generator and its 2400 kW dc exciter. The dc exciting current $I_x$ (6000 A) flows through the commutator and two slip-rings. The dc control current $I_c$ from the pilot exciter permits variable field control of the main exciter, which, in turn, controls $I_x$. 
Number of Poles

The number of poles on a synchronous generator depends upon the speed of rotation and desired frequency.

\[ f = \frac{pn}{120} \]

Where  
- \( f \) = frequency of the induced voltage (Hz)  
- \( p \) = number of poles on the rotor  
- \( n \) = speed of the rotor (rpm)
Synchronous Generator: Stator

• From an electrical standpoint, the stator of a synchronous generator is identical to that of a 3-phase induction motor (cylindrical laminated core containing slots carrying a 3-phase winding).

• The nominal line voltage of a synchronous generator depends upon its kVA rating – the greater the power, the higher the voltage

• The nominal line voltage seldom exceeds 25kV, since the increased slot insulation takes up valuable space at the expense of copper conductors
Synchronous Generator: Stator

Figure 16.2a
Stator of a 3-phase, 500 MVA, 0.95 power factor, 15 kV, 60 Hz, 200 r/min generator. Internal diameter: 9250 mm; effective axial length of iron stacking: 2350 mm; 378 slots.
(Courtesy of Marine Industrie)
Synchronous Generator: Rotor

- **Salient-pole rotors**
  - Used for low speed applications (<300rpm) which require large number of poles to achieve required frequencies (e.g. hydro turbines)

- **Cylindrical rotors**
  - Used for high-speed applications (steam/gas turbines).
  - Minimum number of poles is 2, so for 50Hz the maximum speed is 3000rpm.
  - High speed of rotation produces strong centrifugal forces, which impose upper limit on the rotor diameter.
Synchronous Generator: Rotor

Figure 16.4
This 36-pole rotor is being lowered into the stator shown in Fig. 16.2. The 2400 A dc exciting current is supplied by a 330 V, electronic rectifier. Other details are: mass: 600 t; moment of inertia: 4140 t·m²; air gap: 33 mm. (Courtesy of Marine Industrie)
Synchronous Generator: Rotor
Synchronous Generator: Rotor

Figure 16.7b
Rotor with its 4-pole dc winding. Total mass: 204 t; moment of inertia: 85 t·m²; air gap: 120 mm. The dc exciting current of 11.2 kA is supplied by a 600 V dc brushless exciter bolted to the end of the main shaft.  
(Courtesy of Allis-Chalmers Power Systems Inc., West Allis, Wisconsin)
Field Excitation and Exciters

• DC field excitation is an important part of the overall design of a synchronous generator
• The field must ensure not only a stable AC terminal voltage, but must also respond to sudden load changes – rapid field response is important.
• Main and pilot exciters are used
• Brushless excitation systems employ power electronics (rectifiers) to avoid brushes & slip ring assemblies.
Field Excitation and Exciters

Figure 16.8
Typical brushless exciter system.
No Load Saturation Curve
Figure 16.13
a. Generator operating at no-load.
b. No-load saturation curve of a 36 MVA, 21 kV, 3-phase generator.
Synchronous Reactance

Equivalent circuit of a synchronous generator:

- Each phase has resistance $R$ and inductance $L$
- Synchronous reactance: $X_s = 2\pi f L$
- $R$ is typically $<< X_s$, therefore neglected unless interested in efficiency or heating effects
Determining $X_s$

Open-circuit test:
- Generator run at rated speed
- Exciting current is raised until rated voltage generated
- Exciting current $I_{xn}$ and line-to-neutral voltage $E_n$ are recorded

Short circuit test:
- Excitation is reduced to zero and armature is short-circuited
- Generator run at rated speed
- Excitation returned to value $I_{xn}$
- Short-circuit $I_{sc}$ in the stator is measured

$$X_s = E_n \cdot I_{sc}$$

Synchronous reactance is not constant, but varies with the degree of saturation.
Base Impedance I Per unit $X_s$

Use the rated line-to-line voltage $E_B$
Use the rated power of the generator $S_B$

Base impedance $Z_B = E_B^2 \cdot I S_B$

$X_s$ (per unit) = $X_s \cdot I Z_B$
Synchronous Generator under Load

Two basic load categories:

- Isolated loads supplied by a single generator
- The infinite bus
Synchronous Generator under Load: Isolated Loads
Synchronous Generator under Load: Isolated Loads

Figure 16.20
Phasor diagram for a lagging power factor load.

Figure 16.21
Phasor diagram for a leading power factor load.
Synchronous Generator under Load: Isolated Loads
Figure 16.23
Regulation curves of a synchronous generator at three different load power factors.
Synchronous Generator under Load: Infinite Bus

The infinite bus concept:

- A system so large and powerful that it imposes its own voltage and frequency upon any apparatus connected to its terminals (i.e. the electricity grid)

For synchronous generator to connect to the grid, it must be *synchronised*. 
Synchronous Generator under Load: Infinite Bus

Four conditions for synchronisation:

1. The generator frequency is equal to the system frequency
2. The generator voltage is equal to the system voltage
3. The generator voltage is in phase with the system voltage
4. The phase sequence of the generator is the same as that of the system
Synchronous Generator under Load: Infinite Bus

For a synchronous generator connected to the grid, the magnitude and frequency of the terminal voltage is fixed.

So what determines the power delivered?

There are two parameters that may be varied:

- The exciting current
- The mechanical torque produced by the turbine
Synchronous Generator under Load: Infinite Bus

• Generator floating on an infinite bus:

Figure 16.26a
Generator floating on an infinite bus.
Synchronous Generator under Load: Infinite Bus

Over-excited generator floating on an infinite bus:
Synchronous Generator under Load: Infinite Bus

Under-excited generator floating on an infinite bus:
Synchronous Generator under Load: Infinite Bus

Mechanical torque exerted on the generator:

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Figure 16.27
a. Turbine driving the generator.
b. Phasor diagram showing the torque angle $\delta$. 
Synchronous Generator under Load: Infinite Bus

Torque exerted on the generator:
Synchronous Generator under Load: Infinite Bus

**Figure 16.28a**
The N poles of the rotor are lined up with the S poles of the stator.

**Figure 16.28b**
The N poles of the rotor are ahead of the S poles of the stator.
Synchronous Generator under Load: Infinite Bus

Torque exerted on the generator:

There is a direct relationship between the mechanical angle ($\alpha$) and the torque angle ($\dot{\omega}$):

$$\dot{\omega} = p \alpha \frac{1}{2}$$

- $\dot{\omega}$ = torque angle between the terminal voltage and the excitation voltage (electrical degrees)
- $\alpha$ = mechanical angle between the centres of the stator and rotor poles (mechanical degrees)
- $p$ = number of poles on the generator
Synchronous Generator under Load: Infinite Bus

Active power delivered by the generator:
Synchronous Generator under Load: Infinite Bus

$P_{\text{max}} = \frac{E_0 E}{X_s}$

**Figure 16.29**
Graph showing the relationship between the active power delivered by a synchronous generator and the torque angle.
Synchronous Motors

Synchronous motors are essentially a synchronous generator running in reverse.

Motor rotates at synchronous speed – to vary the speed, the supply frequency must be varied.

By varying the excitation at varying active power loads, the power factor can be adjusted (to $1$ if desired).
Synchronous vs. Induction Motors

Induction motors have excellent properties for higher speeds. But at lower speeds they become heavy, costly and have relatively low power factors and efficiencies.

Synchronous motors are particularly attractive for low-speed drives since the power factor can be adjusted to 1 and the efficiency is high. Although more complex to build, their weight and cost are often less than those of induction motors of equal power and speed.
Factors effecting the efficiency, power and size of electrical machines

The physical size of an electrical machine has a profound effect upon its efficiency, power output, relative cost and temperature rise.

- Suppose we increase the size of a machine such that its linear dimensions are scaled in exactly the same proportion, meanwhile using the same materials.
- Retain the same current densities and flux densities
- Copper losses and iron losses per unit volume will be the same.
- Furthermore, assume that no. of slots and conductors remain the same, and that rotating speed (rpm) is unchanged.

Assume that linear dimensions are increased by $K$:

- Volume and mass increases by $K^3$ – losses increase by $K^3$ too.
- Slots are $K$ times wider and deeper – therefore conductor cross section increases by $K^2$, current rating increases by $K^2$ too.
- For generated voltage, length increases by $K$, peripheral speed increases by $K$ – voltage generated increases by $K^2$.
- Power rating increases by $K^4$, whereas losses increase by $K^3$.
- Power density and efficiency go up!
Factors effecting the efficiency, power and size of electrical machines

Everything seems to favour increasing the machine size.

But the big problem with increasing the size is temperature rise!

• If dimensions increase by $K$, then losses increase by $K^3$, but heat-dissipating surface area only increases by $K^2$.
• Therefore larger machines need more effective cooling.

Ultimately, a point is reached where the increased cost of cooling exceeds the savings from better power density and efficiency – this fixes the upper limit to the size.

This analysis applies to all electrical machines (motors and transformers)